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# Evaluations of the $^{239}\text{Pu}$ Fission Source Term

Denise Neudecker

Internal Pu working group meeting, 5/2021

Thanks to: M.B. Chadwick, M. Devlin,  
K. Kelly, R.C. Little, A. Lovell,  
P. Marini, L. Snyder, J. Taieb, P. Talou.

# $^{239}\text{Pu}(\text{n},\text{f})$ PFNS evaluation



PFNS

nu-bar

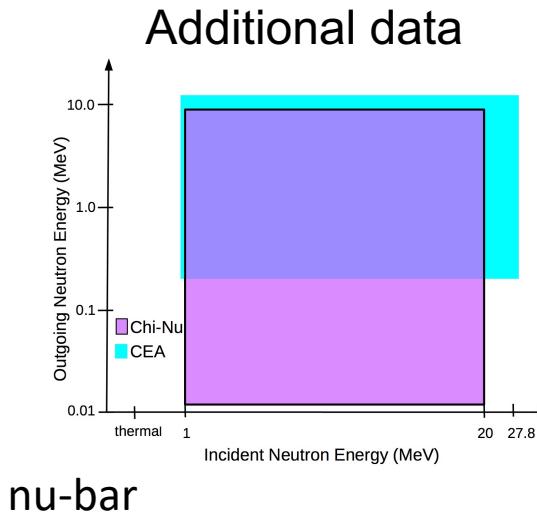
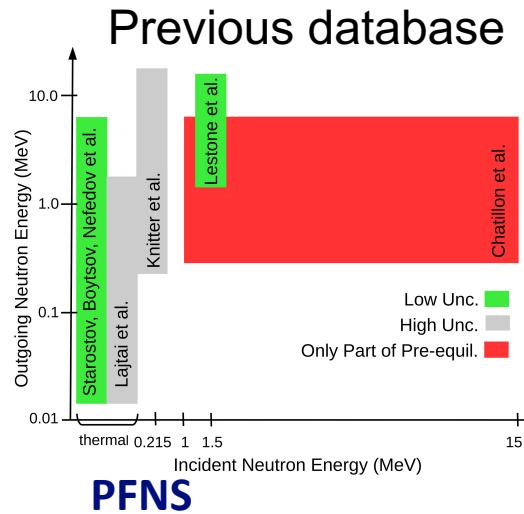
(n,f) cross section

5/6/21

2

# $^{239}\text{Pu}(n,f)$ PFNS is being re-evaluated to include new model and high-impact Chi-Nu (LANL-led) and CEA exp. data.

- NCSP Deliverable FY21: “Evaluate PFNS and multiplicity consistently, including angular information about prompt neutrons”.
- Co-funded by ASC-PEM-NP.
- Motivation for re-visit:
  - Include high-impact Chi-Nu and Marini (CEA) PFNS (high-precision, large energy-range),
  - Implement CGMF model (with Amy Lovell).



Both data sets were taken at LANSCE with the Chi-Nu array as part of a NNSA/CEA collaboration.

(n,f) cross section



# $^{239}\text{Pu}$ PFNS evaluation: This was a bit of a longer journey with many challenges ... not sure if I am close to the finish-line.

Experimental data: CEA provided distinctly smaller unc. for a measurement with nearly the same equipment as Chi-Nu and lower statistics ->

- increased unc. with templates,
- corrected mv for ratio-measurement effect (K. Kelly et al., NIMA, accepted), ->
- explained some of the systematic differences.

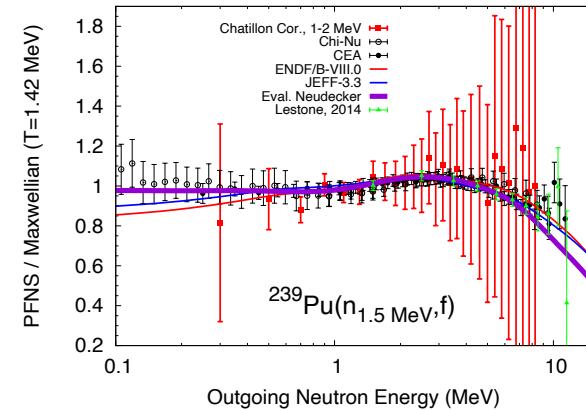
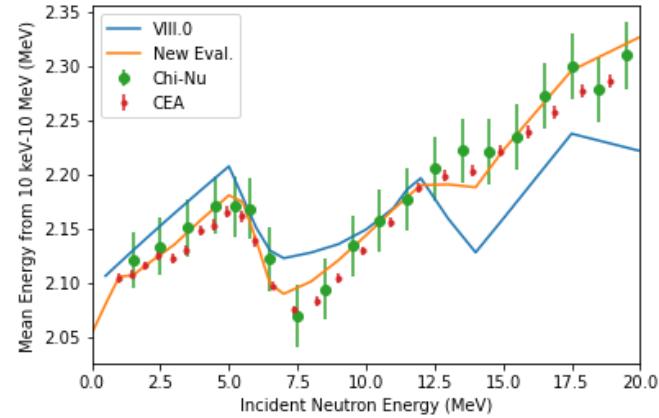
## Evaluation:

1. systematic LAM evaluation for  $E_{\text{inc}}$  = thermal to 30 MeV -> PFNS  $E_{\text{inc}} = 1.5 \text{ MeV}$ ,  $E_{\text{out}} > 8 \text{ MeV}$  deviated from exp. due to model cor. ->
2. Mark asked for separate LAM evaluations for  $E_{\text{inc}} = 0.5$ - 2 MeV (no cor. between PFNS at different  $E_{\text{inc}}$ ).



(n,f) cross section

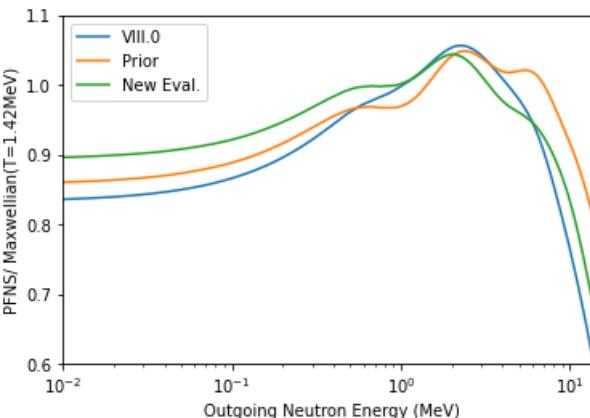
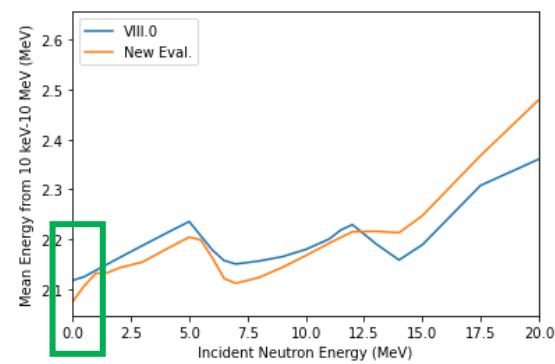
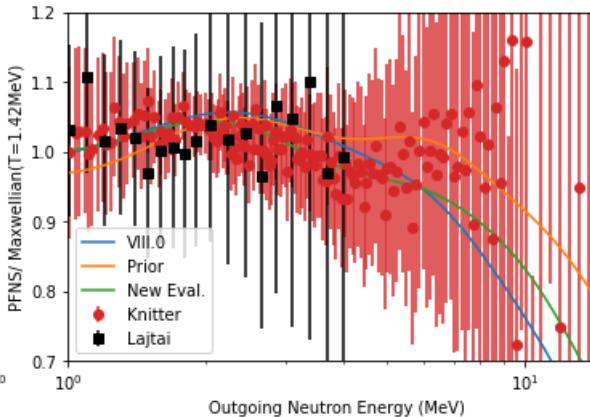
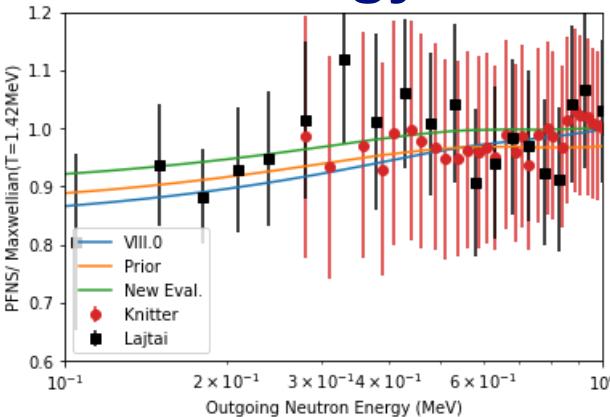
nu-bar



PFNS

5/6/21

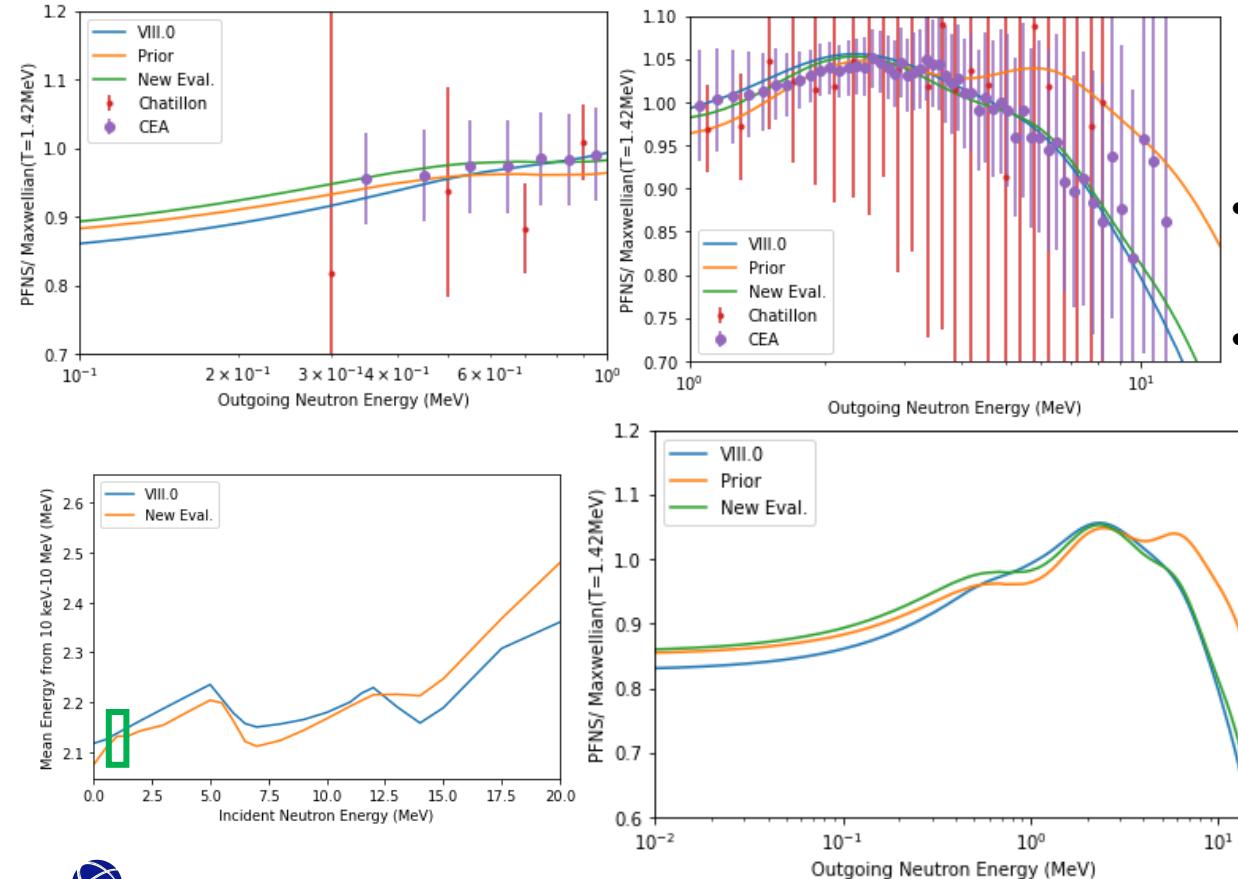
# Current version: $^{239}\text{Pu}(n,f)$ PFNS $E_{\text{inc}} = 500 \text{ keV}$ , Mean energy: 2.106 MeV



- Prior: LAM with 6% normalization uncertainty.
- Experimental data:
  - Knitter at  $E_{\text{inc}} = 1.5 \text{ MeV}$ ,
  - Lajtai at  $E_{\text{inc}} = \text{thermal}$  (only for extending to lower  $E_{\text{out}}$ , very large unc.).



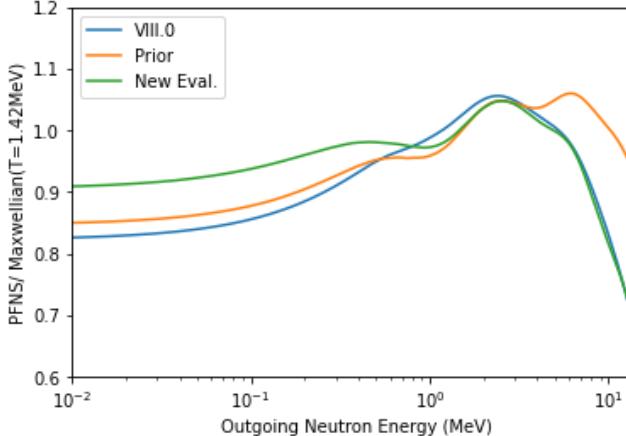
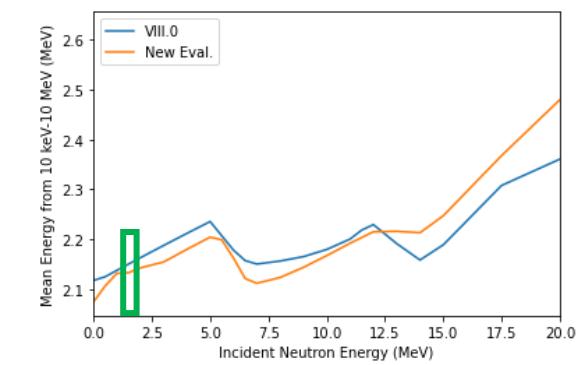
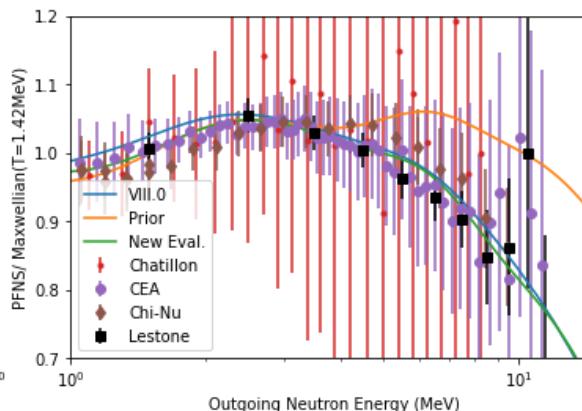
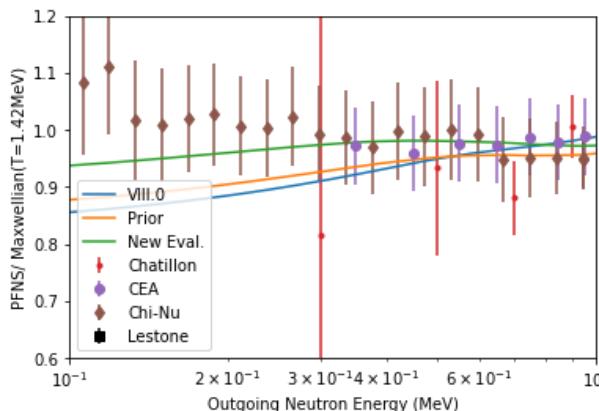
# $^{239}\text{Pu}(n,f)$ PFNS $E_{\text{inc}} = 1 \text{ MeV}$ , Mean energy: 2.131 MeV



- Prior: LAM with 6% normalization uncertainty.
- Experimental data:
  - CEA (mean values corrected, enlarged unc. in wings, approximate cov.),
  - Chatillon at  $E_{\text{inc}} = 1.5 \text{ MeV}$ .



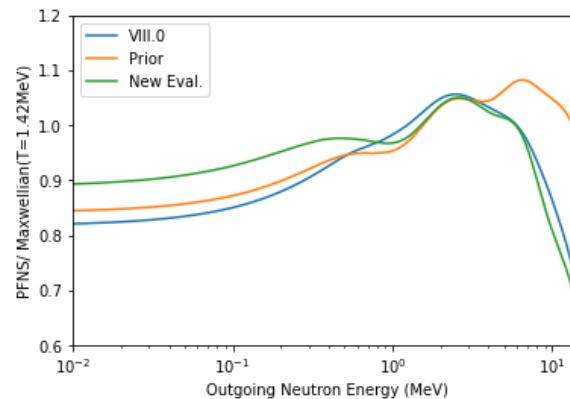
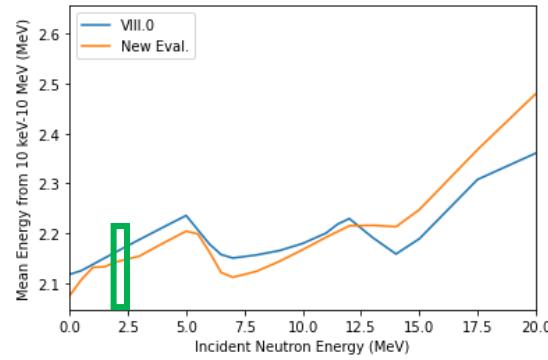
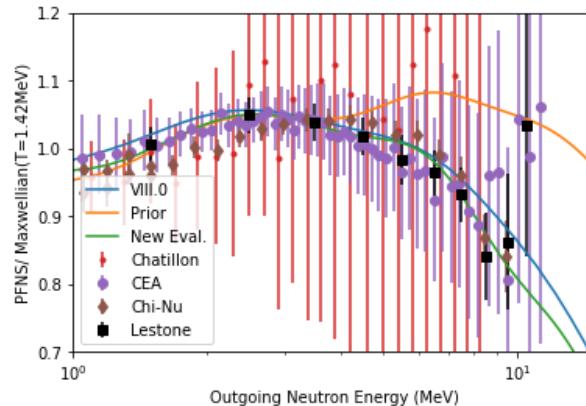
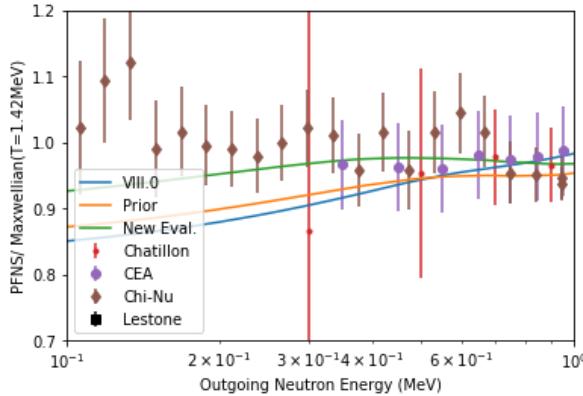
# $^{239}\text{Pu}(n,f)$ PFNS $E_{\text{inc}} = 1.5$ MeV, Mean energy: 2.133 MeV



- Prior: LAM with 6% normalization uncertainty.
- Experimental data:
  - CEA (mean values corrected, enlarged unc. in wings, approximate cov.),
  - Chi-Nu (approximate cov.),
  - Lestone at  $E_{\text{inc}} = 1.5$  MeV,
  - Chatillon at  $E_{\text{inc}} = 1.5$  MeV.



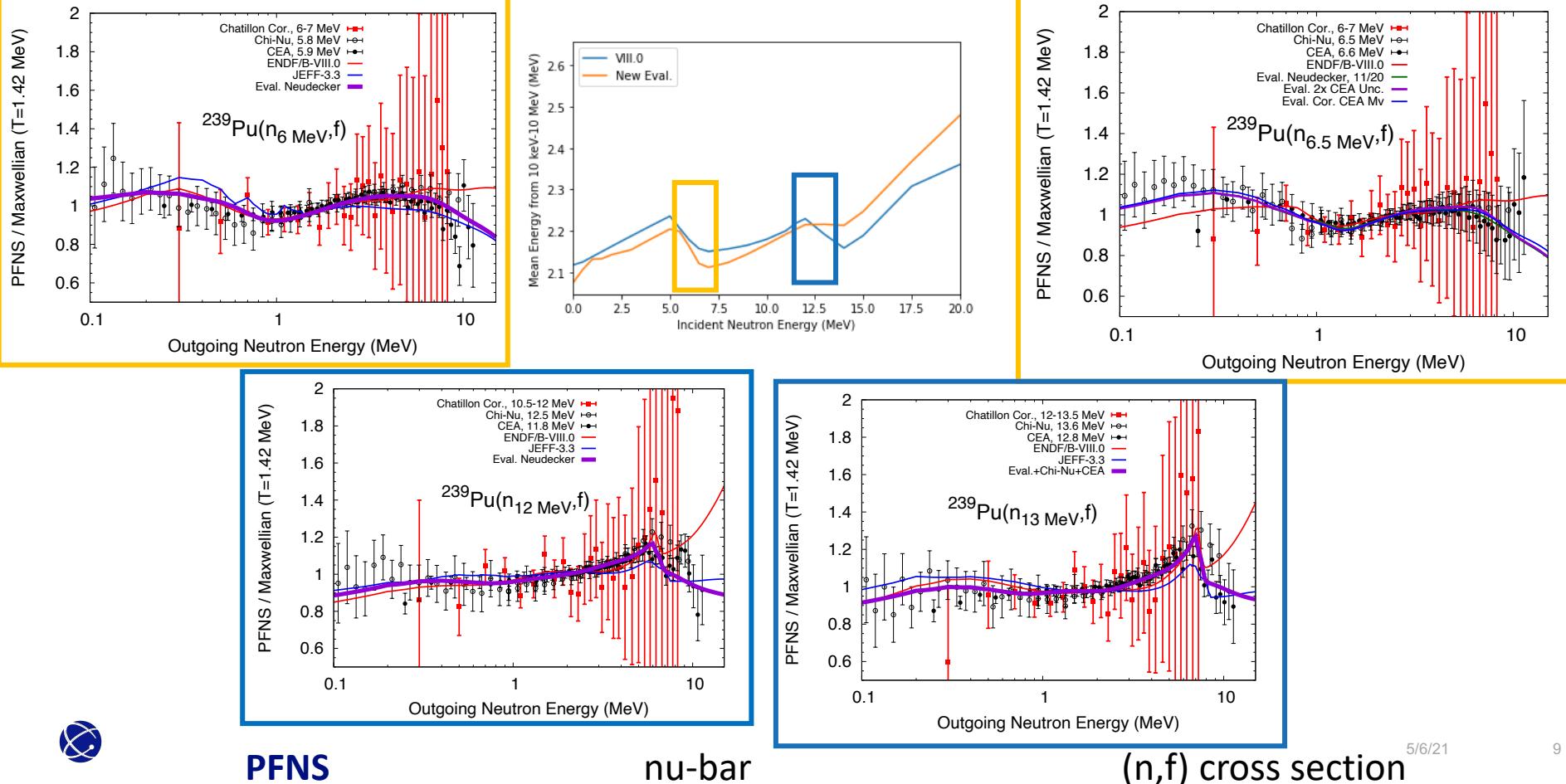
# $^{239}\text{Pu}(n,f)$ PFNS $E_{\text{inc}} = 2$ MeV, Mean energy: 2.142 MeV



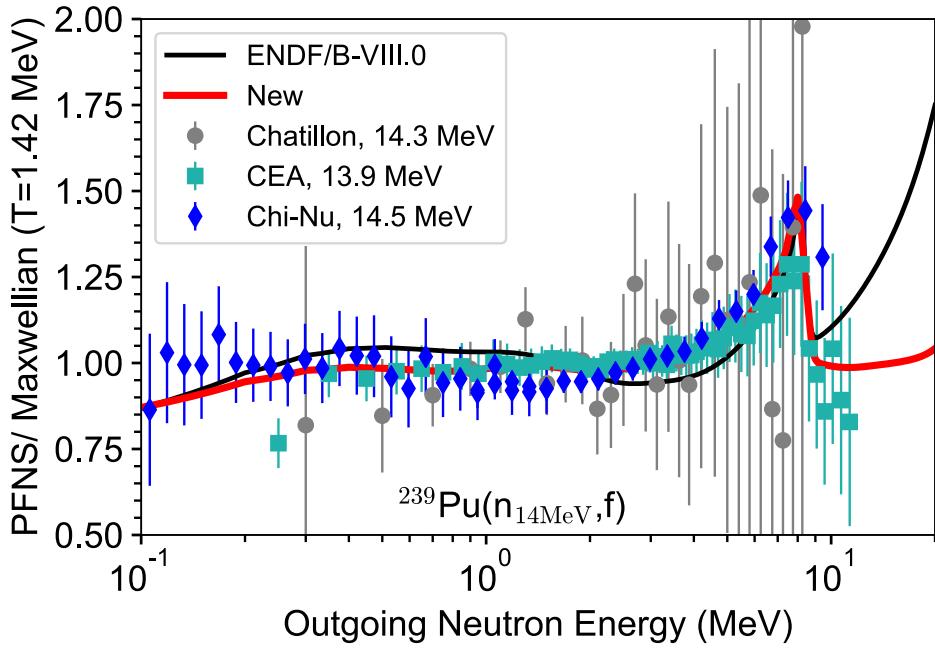
- Prior: LAM with 6% normalization uncertainty.
- Experimental data:
  - CEA (mean values corrected, enlarged unc. in wings, approximate cov.),
  - Chi-Nu (approximate cov.),
  - Lestone at  $E_{\text{inc}} = 2$  MeV,
  - Chatillon at  $E_{\text{inc}} = 2.5$  MeV.



# Chi-Nu & CEA change eval. , show physics features better.



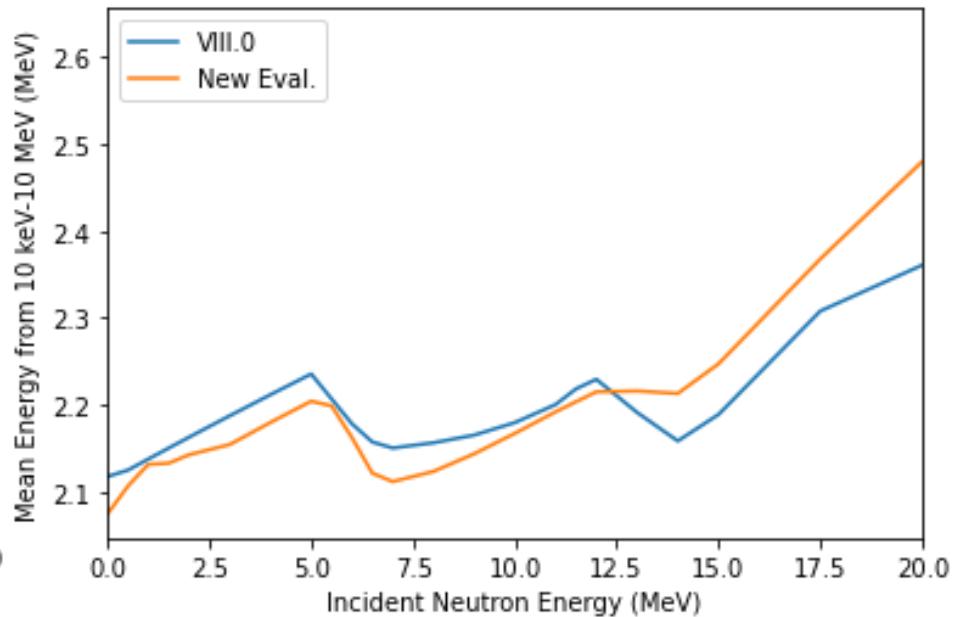
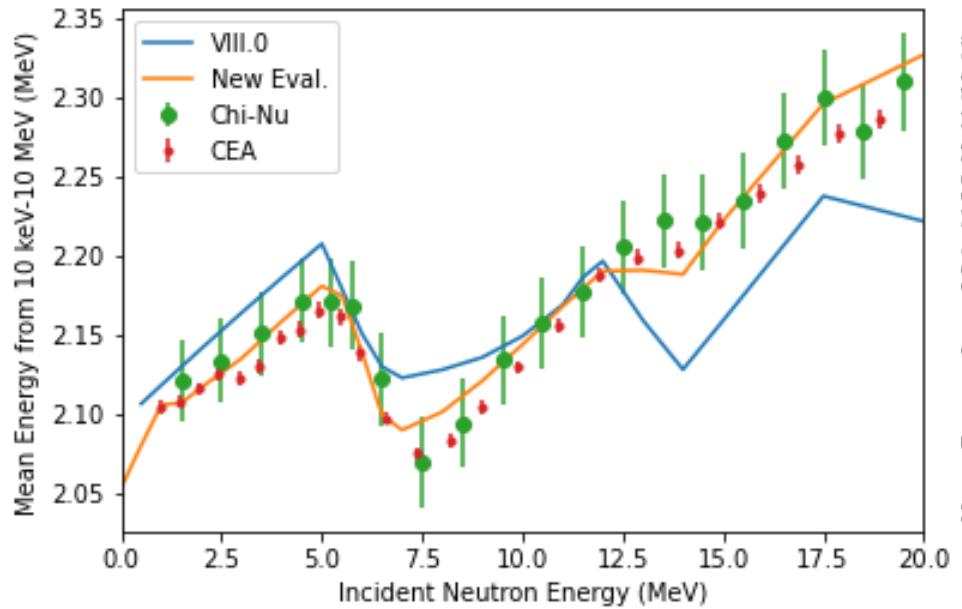
# $^{239}\text{Pu}(n,f)$ PFNS $E_{\text{inc}} = 14$ MeV, Mean energy: 2.213 MeV



- Evaluation from 3-30 MeV.
- Prior: LAM with 6% normalization uncertainty.
- Experimental data:
  - CEA (mean values corrected, enlarged unc. in wings, approximate cov.),
  - Chi-Nu (approximate cov.),
  - Chatillon.



# Mean energy continuity not as great due to evaluating separately at $E_{\text{inc}}=0.5\text{-}2 \text{ MeV}$ but agrees with exp. data:



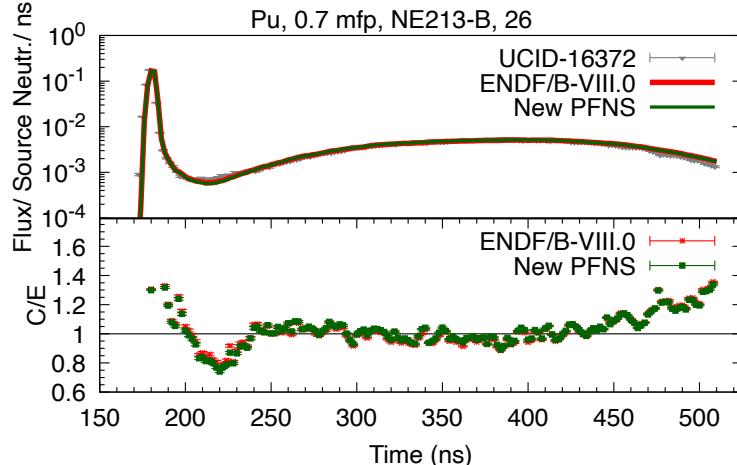
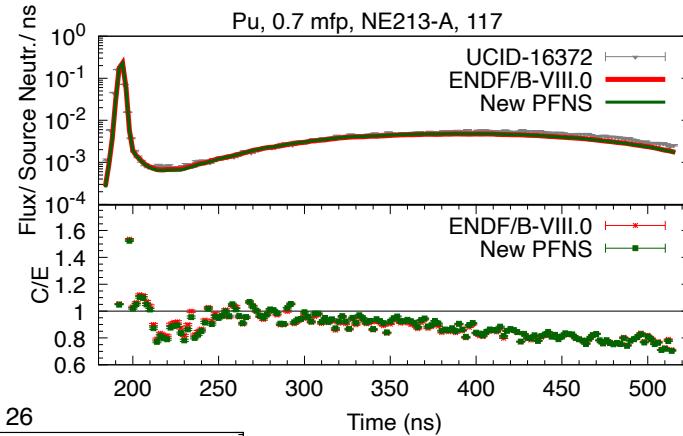
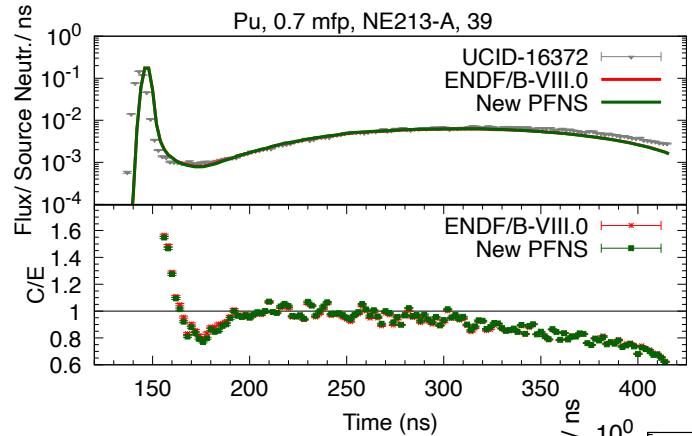
# Benchmarking (green: change within VIII.0+ MC unc., red: change outside of VIII.0+MC unc., unc. on last digit).

Jezebel	Keff	Pu9(n,2n)/(n,f)	Pu9(n,g)/(n,f)	U8/U5(n,f)	Np/U5(n,f)	U3/U5(n,f)	Pu9/U5(n,f)
VIII.0	1.00069(1)	0.00230(5)	0.0345(2)	0.212(1)	0.9768(5)	1.566(7)	1.427(6)
new PFNS	0.99941(1)	0.00225(5)	0.0354(2)	0.209(1)	0.9660(5)	1.566(7)	1.424(6)
Exp.	1.0000(11)			B 0.2133 (23) A 0.2137(23)	0.9835(14) 0.9620(16)	1.578(27)	1.4609(130) 1.448(29)

Flattop-Pu	Keff	Pu9(n,2n)/(n,f)	Pu9(n,g)/(n,f)	U8/U5(n,f)	Np/U5(n,f)
VIII.0	0.99971(1)	0.00197(4)	0.0455(1)	0.1800(9)	0.8591(4)
VIII.0+new PFNS	0.99857(1)	0.00193(4)	0.0464(1)	0.1775(9)	0.8499(4)
Exp.	1.0000(16)			0.1492(16) 0.149(2)	0.7804(100) 0.76(1)

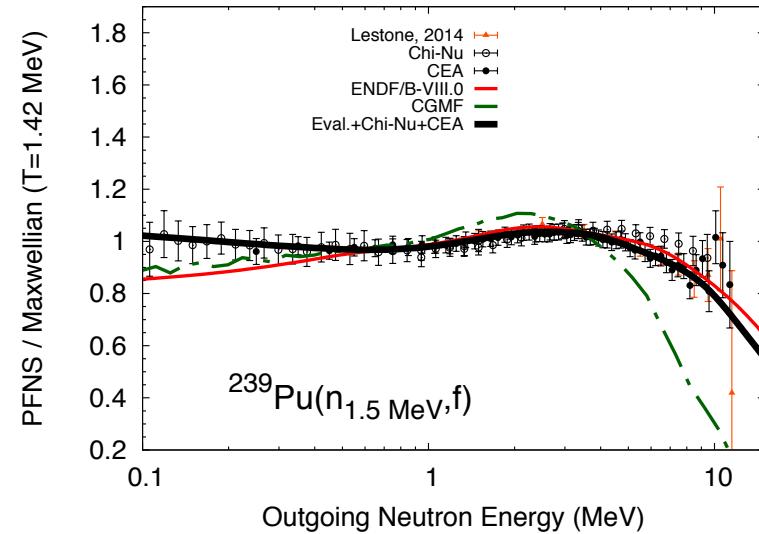


# Benchmarking Pulsed Spheres: little change.



# To-do: CGMF inclusion and maybe more iterations on LAM????

- Current and one previous evaluation were delivered to INDEN on Mark's request,
- Maybe another round of LAM evaluation???? -> depending on benchmarking results from INDEN,
- Including CGMF model via Kalman filter. This will include CGMF modeling an sensitivities from Amy Lovell. **Major challenge.**

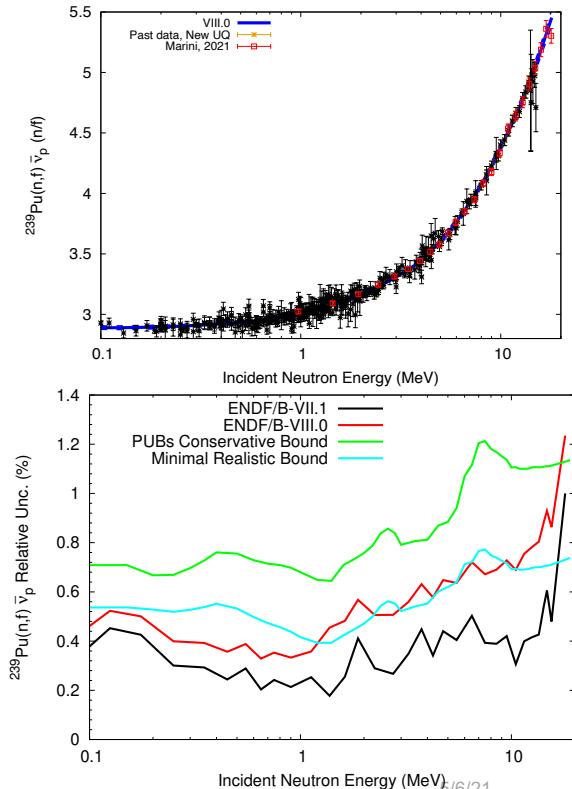


# **$^{239}\text{Pu}(\text{n},\text{f})$ nu-bar evaluation**

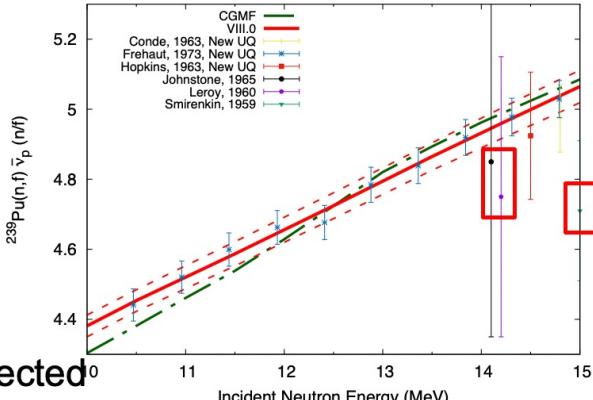
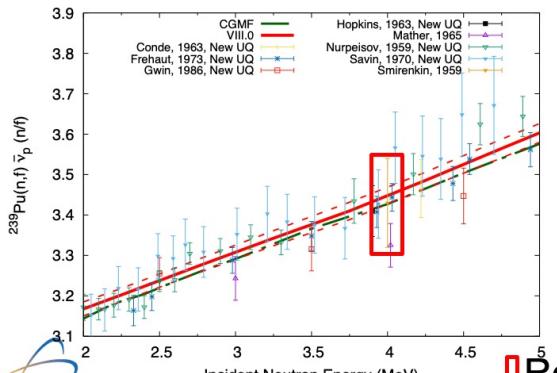
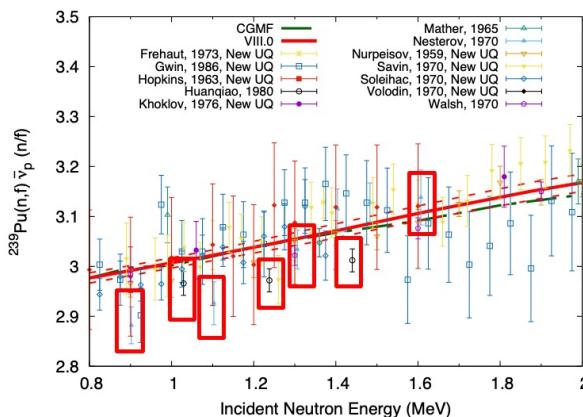
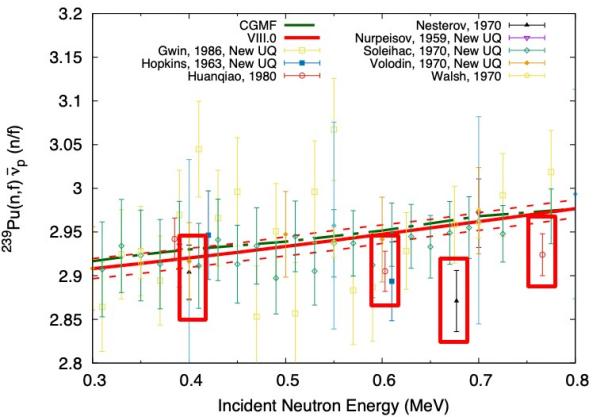


# $^{239}\text{Pu}(n,f)$ nu-bar is being re-evaluated to include new model, experimental data, and improve uncertainty estimate.

- NCSP Deliverable FY21: “Evaluate PFNS and multiplicity consistently, including angular information about prompt neutrons”.
- Co-funded by ASC-PEM-NP.
- Motivation for re-visit:
  - VIII.0 nu-bar unc. likely too small,
  - New data by Marini et al. (CEA) from 1-700 MeV, unc.: 0.5-1.2%, past data used liquid-scintillator technique, these data extracted from PFNS,
  - Implement CGMF model (with Amy Lovell).
- Plan forward:
  - Re-produce previous mean value for consistency,
  - Experiments: include new data, better UQ,
  - Model: include CGMF.



# Step 1: Revisit uncertainties of past data using templates of expected measurement uncertainties - DONE



nu-bar

(n,f) cross section

Rejected

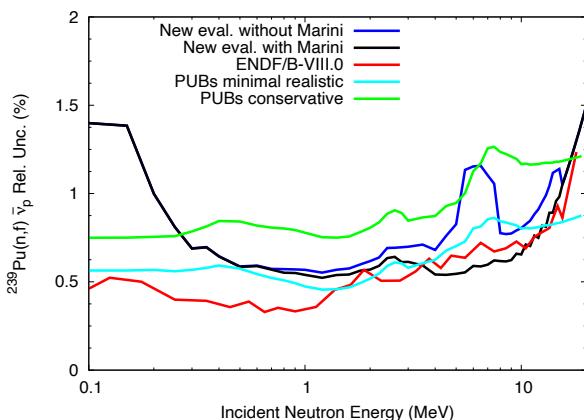
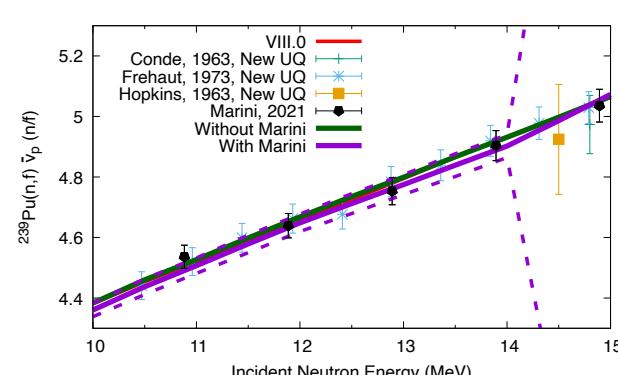
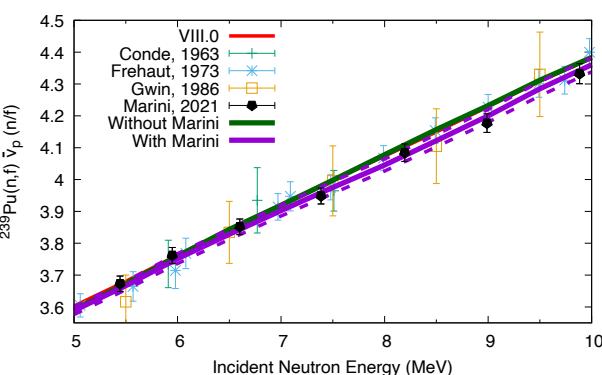
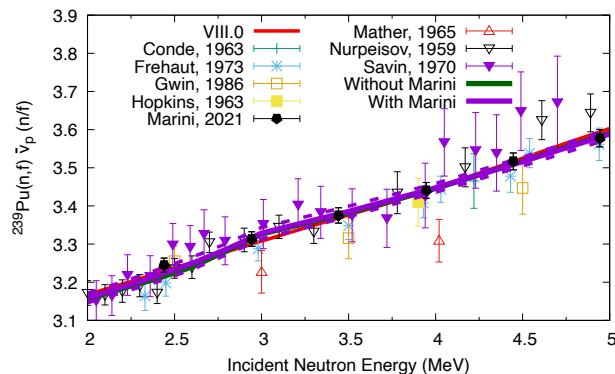
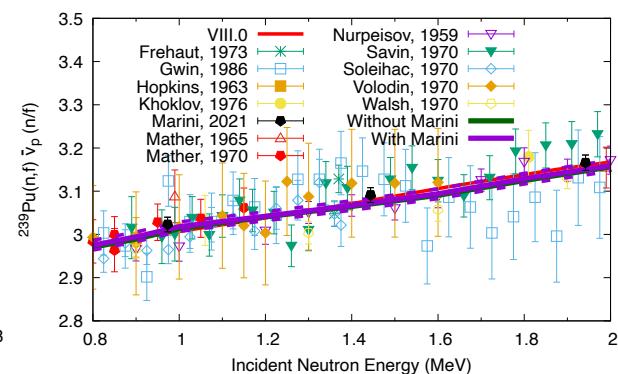
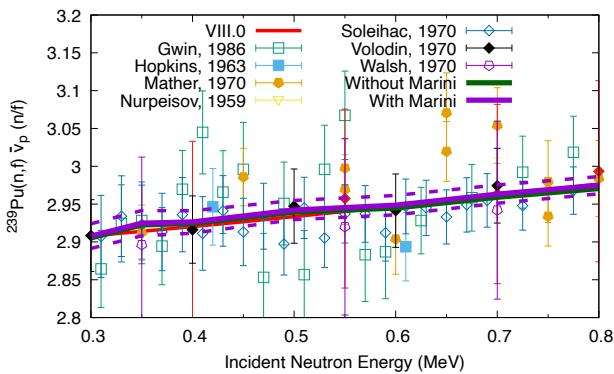


PFNS

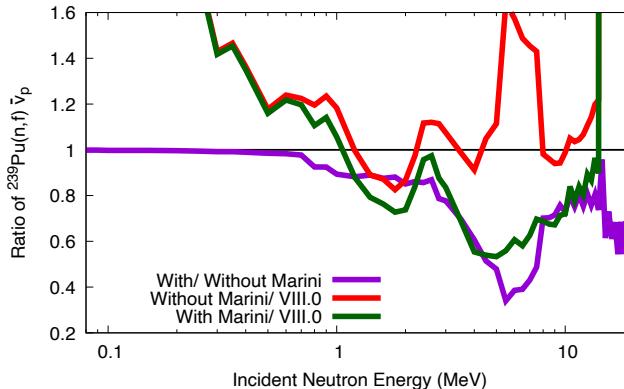
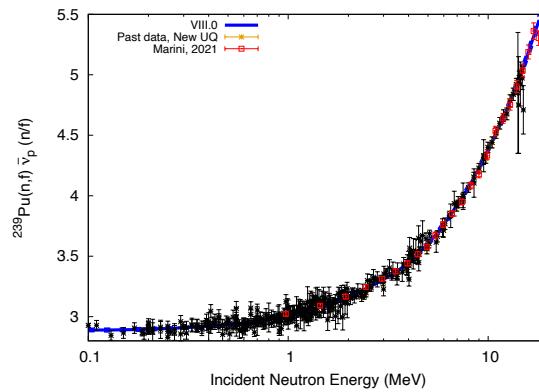
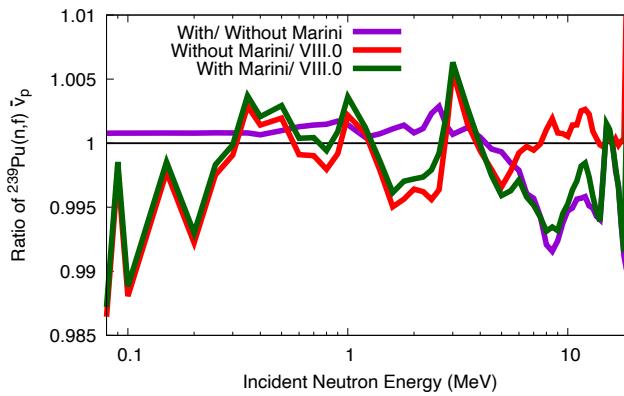
Changes compared to Phil's evaluation:

- Used templates to identify missing uncertainties and correlation functions for unc.,
- Rejected a few data sets with little impact,
- PPP correction implemented in ARIADNE.

# Step 1: We reproduced ENDF/B-VIII.0 $^{239}\text{Pu}(n,f)$ prompt nu-bar data and obtain more realistic eval. uncertainties.



# Step 2: Included Marini, 2021 et al. data & studied impact. Mean values change > 5 MeV, evaluated unc. reduced.

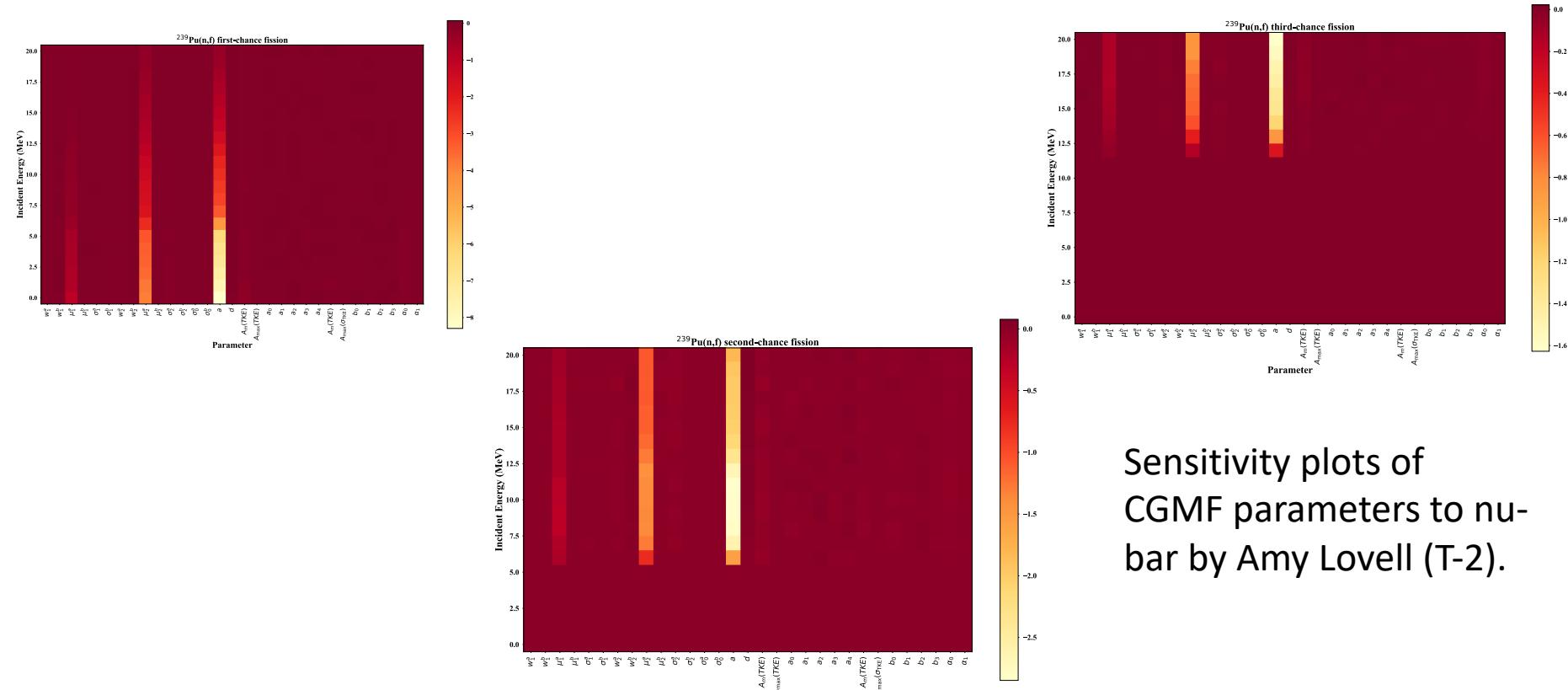


## Marini data:

- They employ a novel technique using the Chi-Nu array, past data all used the liquid-scintillator technique -> validation of previous data -> very encouraging,
- Unc. of past data were often dominated by large statistical unc., CEA has high counting-statistics -> decreases evaluated uncertainties.



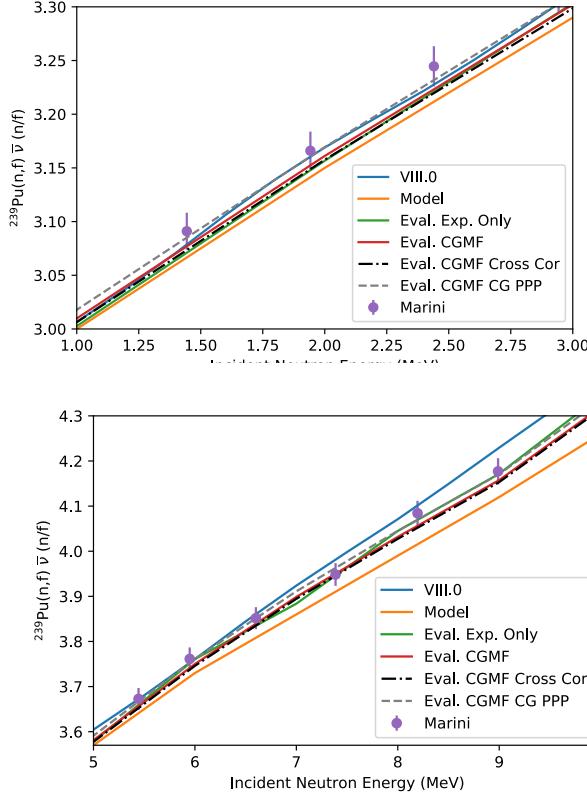
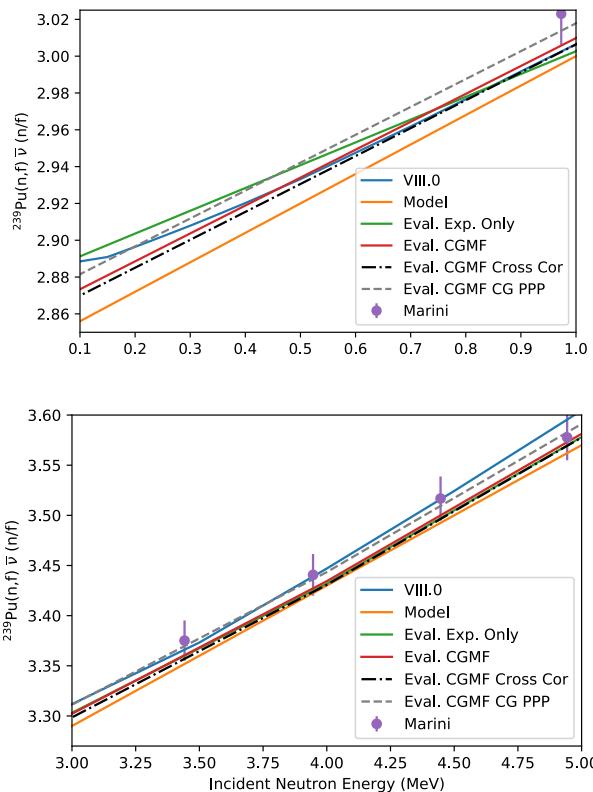
# Step 3: Including CGMF model via Kalman filter, Modeling and sensitivities provided by Amy Lovell.



Sensitivity plots of CGMF parameters to nu-bar by Amy Lovell (T-2).



# Step 3: Including CGMF model via Kalman filter -> first results look promising.

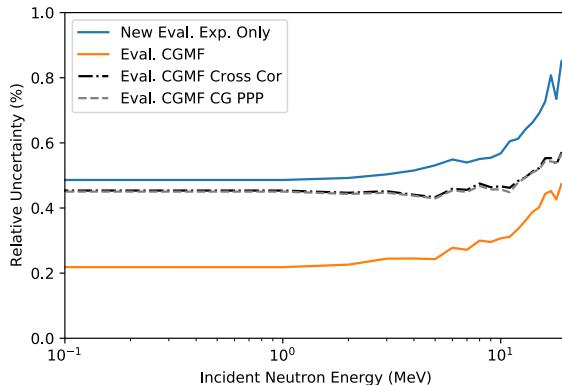
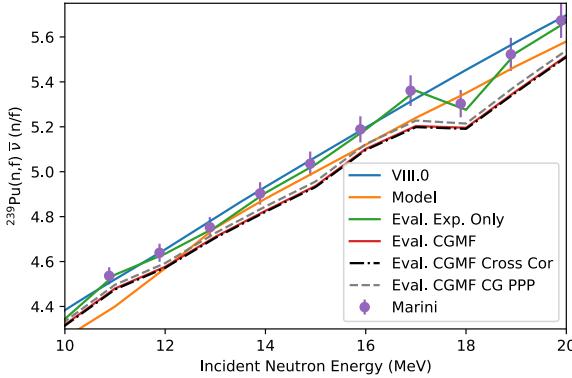


- Prior: CGMF via sensitivities from Amy.
  - Experimental data:
    - Nearly all data that Phil took into account,
    - Marini,
    - Correlation between different exp. (0.42%).
- Kalman:
- with (Eval. CGMF CG PPP) and without (Eval. CGMF Cross Cor) PPP correction by Chiba-Smith,
  - with & without (Eval. CGMF) cross-cor between exp.



# Step 3: Including CGMF model is still work in progress.

## Need to test out a couple of things.



### To-Do:

- Fix PPP code -> DONE,
- Testing out larger unc. for CGMF parameters,
- 2-step evaluation: (1) fix 1<sup>st</sup> chance fission parameters with evaluation  $\leq 5$  MeV, (2) evaluate again with 1<sup>st</sup> c.f. parameters fixed -> currently being worked on,
- Using down-selected list of parameters,
- Including a few more points at lower Einc via explicitly giving sensitivities -> Amy provided data, need to do re-evaluation.



# **$^{239}\text{Pu}(\text{n},\text{f})$ cross section evaluation**



# $^{239}\text{Pu}/^{235}\text{U}(\text{n},\text{f})$ cross sections by niffteTPC were included in Neutron Data Standards' database

- NCSP Deliverable FY21: "Update fission cross section based on TPC results (from  $^{239}\text{Pu}/^{235}\text{U}$  ratio data)" → Snyder et al., to be submitted to NDS. (high-precision ( $\text{n},\text{f}$ ) cross-section exp. campaign led by LLNL, executed at LANSCE)
- NCSP Deliverable FY20: "Update fission cross section based on TPC results (from  $^{238}\text{U}/^{235}\text{U}$  ratio data)" → Casperson et al., PRC 97, 034618 (2018)
- Why do these data matter:
  - TPC data employ new type of fission detector possibly uncovering systematic issues in wealth of previous exp. data mostly measured with fission chambers
  - High-precision measurement explores uncertainty source

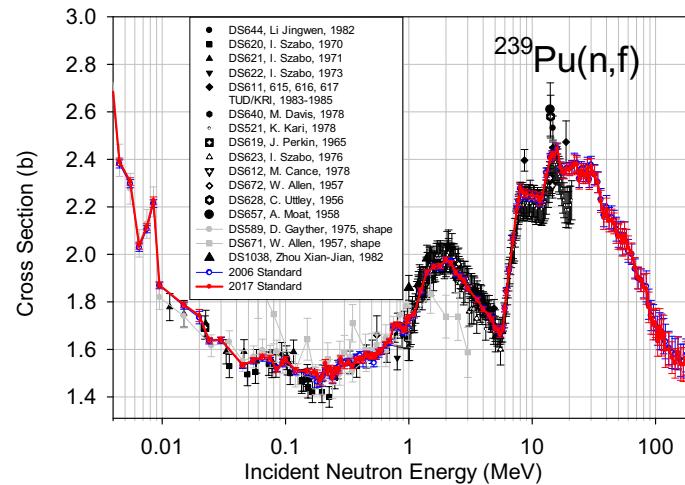


Fig. from Carlson et al., NDS 148, 143 (2018).

(n,f) cross section



# $^{239}\text{Pu}/^{235}\text{U}(\text{n},\text{f})$ cross sections by niffteTPC were included in Neutron Data Standards' database

- NCSP Deliverable FY21: "Update fission cross section based on TPC results (from  $^{239}\text{Pu}/^{235}\text{U}$  ratio data)" → Snyder et al., to be submitted to NDS.

- NCSP Deliverable FY20: "Update fission cross section based on TPC results (from  $^{238}\text{U}/^{235}\text{U}$  ratio data)" → Casperson et al., PRC 97, 034618 (2018)

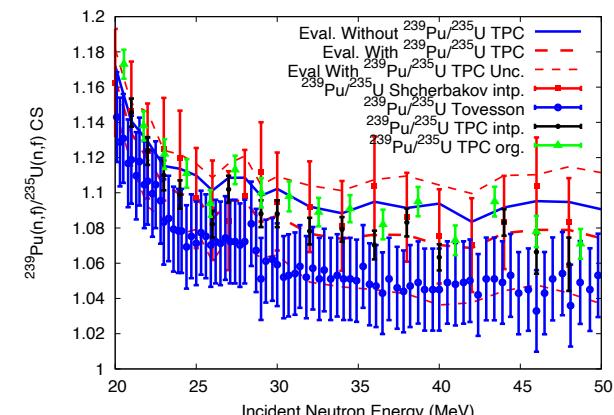
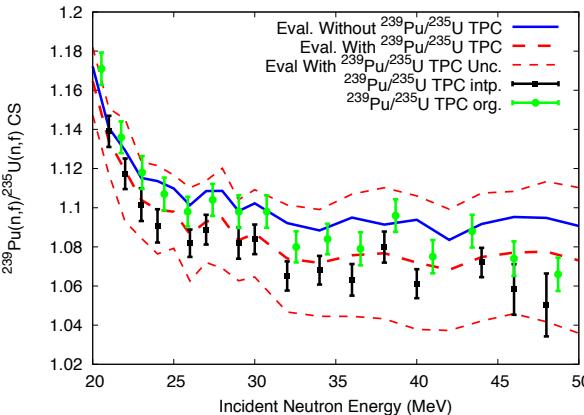
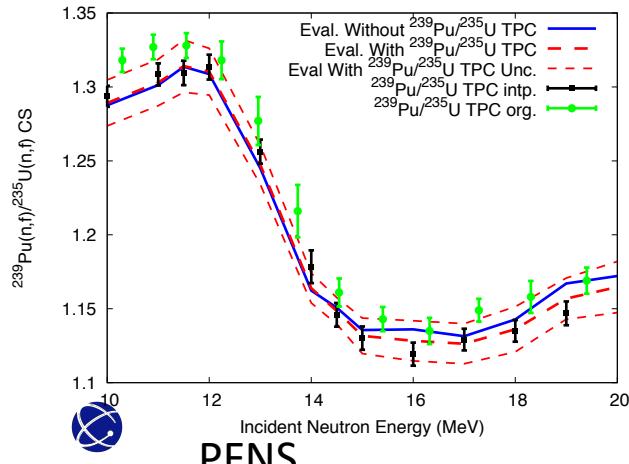
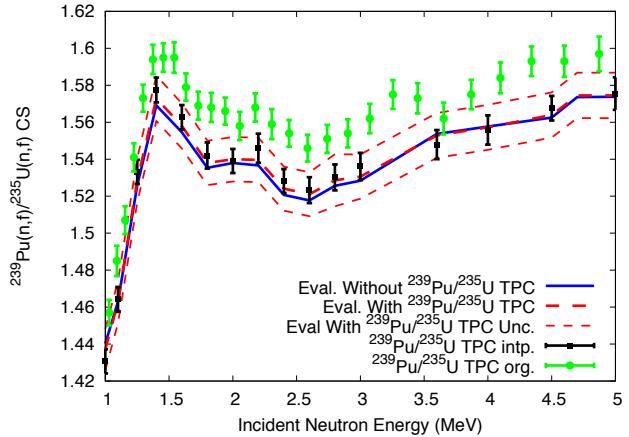
- Why do these data matter:

- TPC data employ new type of fission detector possibly uncovering systematic issues in wealth of previous exp. data mostly measured with fission chambers
  - High-precision measurement explores uncertainty source

See back-up slides.



# $^{239}\text{Pu}/^{235}\text{U}$ (n,f) niffteTPC data significantly change nuclear data > 10 MeV and raise questions about past data.

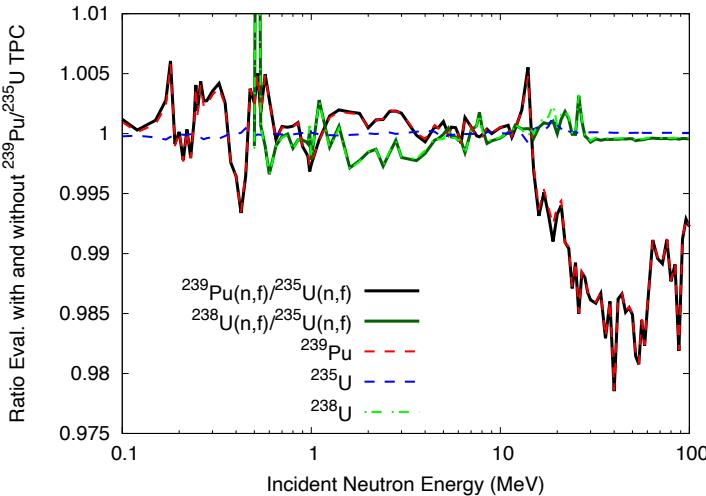


PFNS

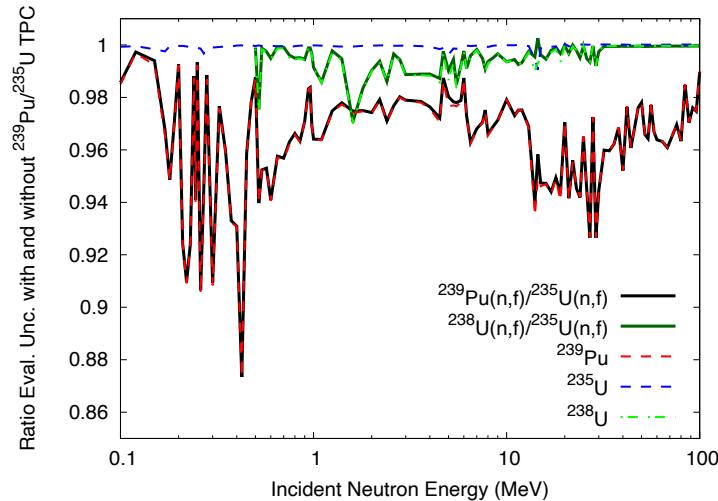
nu-bar

(n,f) cross section

# niffteTPC exp. results change nuclear data < 10 MeV within 0.5% and reduce unc. up to 12%.



niffteTPC data  
mostly impact  
 $^{239}\text{Pu}(n,f)$  and  
 $^{238}\text{U}(n,f)$  cs.



## To-Do:

- Prepare final report for standards, - DONE (LA-UR-21-24093)
- Finalize inclusion with Neutron Data Standards committee,
- Re-visit discussion on previous data > 10 MeV,
- ***Need help on including it into ENDF-file and benchmarking.***



# Summary

- $^{239}\text{Pu}/^{235}\text{U}(\text{n},\text{f})$  niffteTPC data included into standards.
- $^{239}\text{Pu}(\text{n},\text{f})$  nu-bar re-evaluated with more realistic uncertainties and including recent CEA data.
- $^{239}\text{Pu}$  PFNS by Chi-Nu and CEA included.

These new exp. data partially change our understanding of nuclear data. We will need to carefully study benchmark simulations once the evaluations are final.

## To-Do:

- Inclusion of CGMF model into nu-bar and PFNS evaluations,
- Include  $^{235}\text{U}$  Chi-Nu PFNS,
- $^{235}\text{U}(\text{n},\text{f})$  nu-bar evaluation.
- Benchmarking.

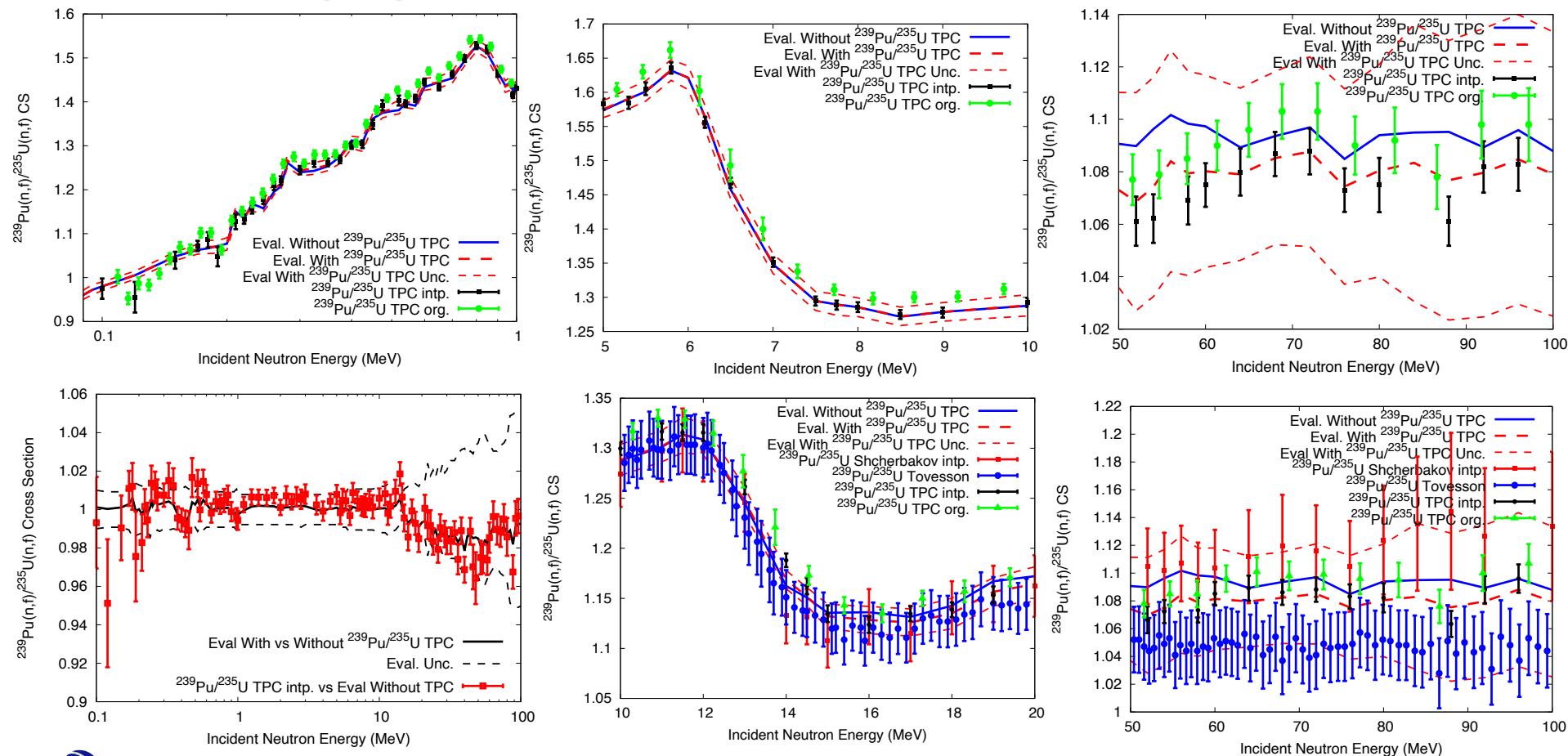
*Thank you for your attention!*

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We gratefully acknowledge the support of the Advanced Simulation and Computing (ASC) program at Los Alamos National Laboratory.



# $^{239}\text{Pu}/^{235}\text{U}(\text{n},\text{f})$ niffteTPC data included in standards

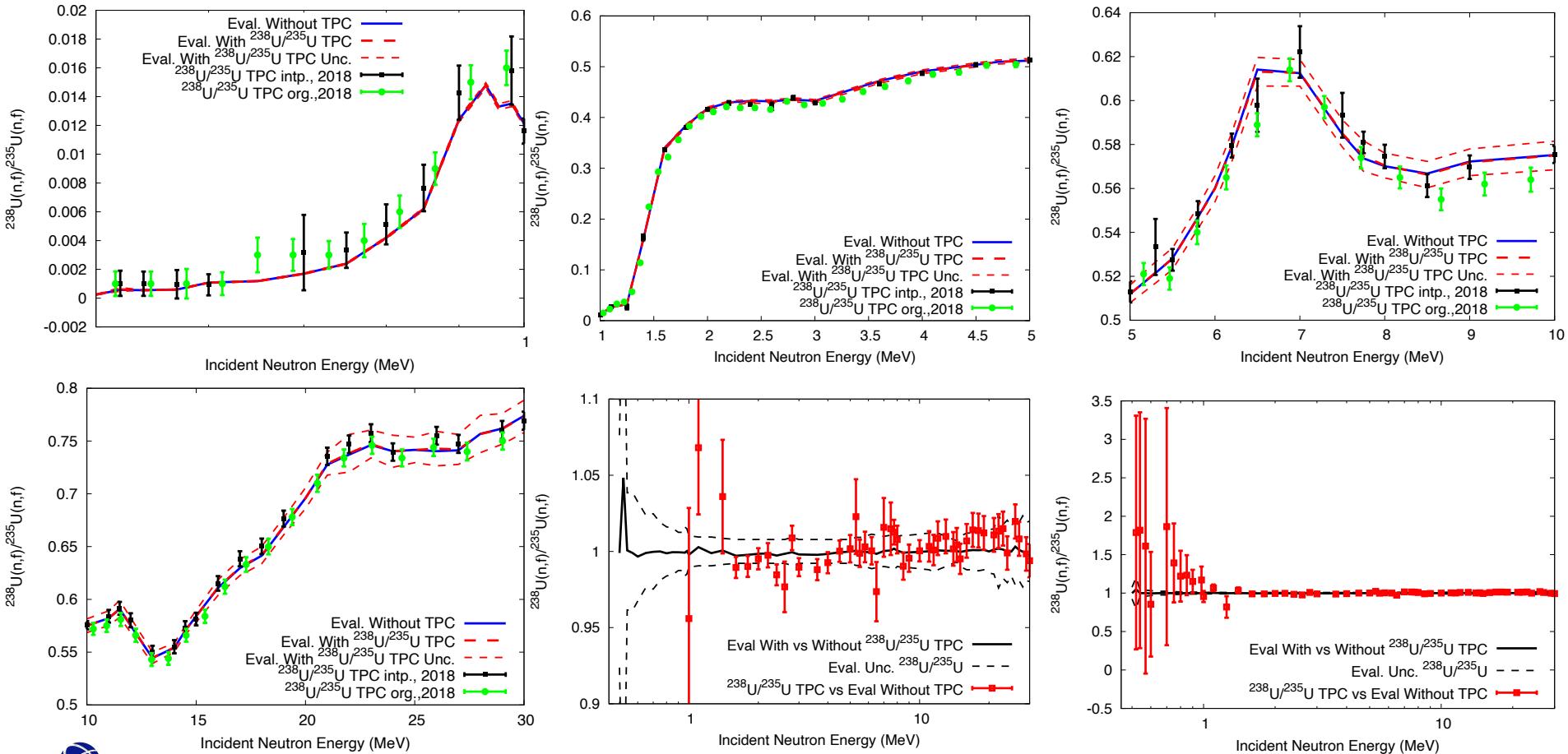


Backup (n,f) cross section

nu-bar

PFNS

# $^{238}\text{U}/^{235}\text{U}(\text{n},\text{f})$ final niffteTPC data included in standards

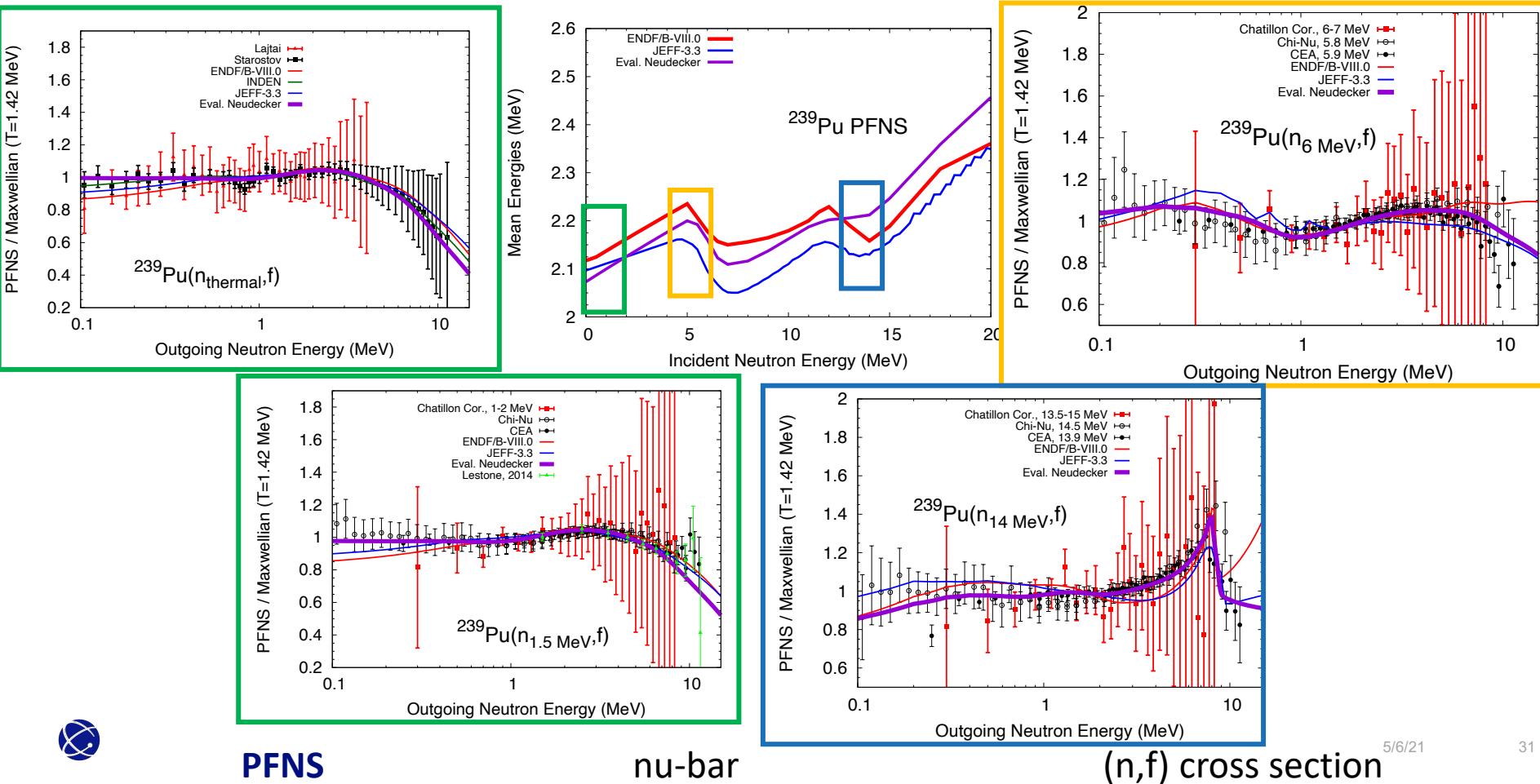


Backup (n,f) cross section

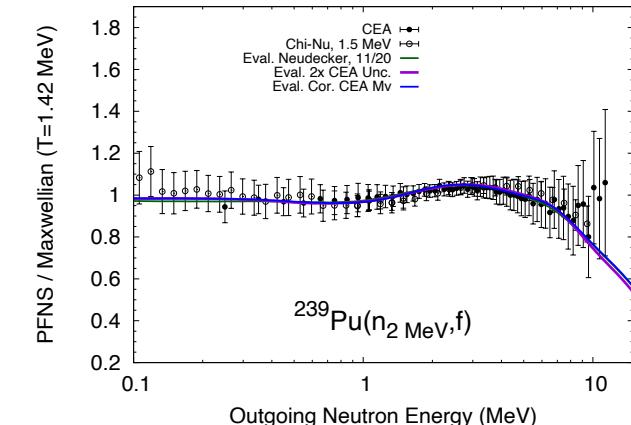
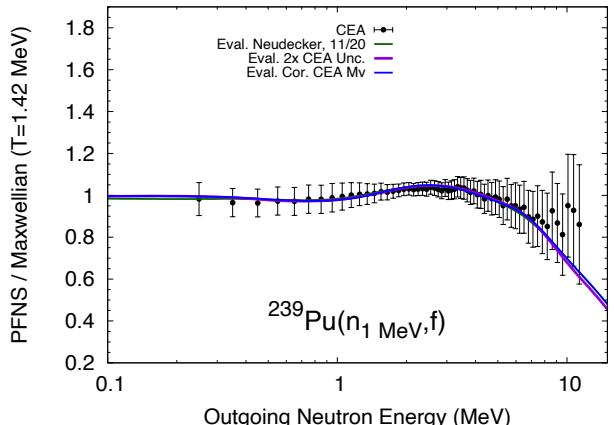
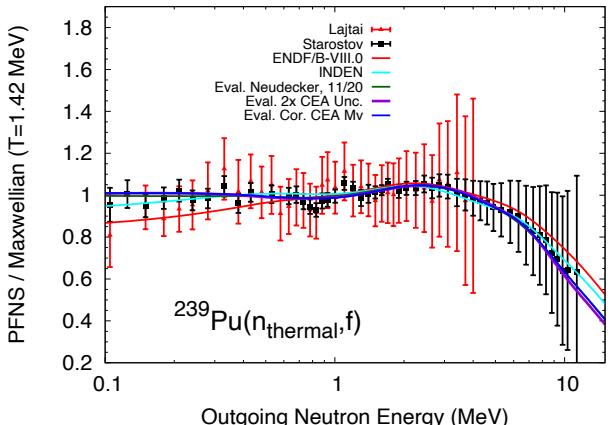
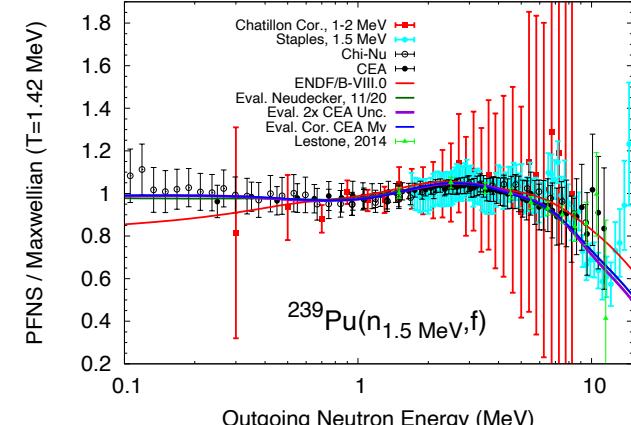
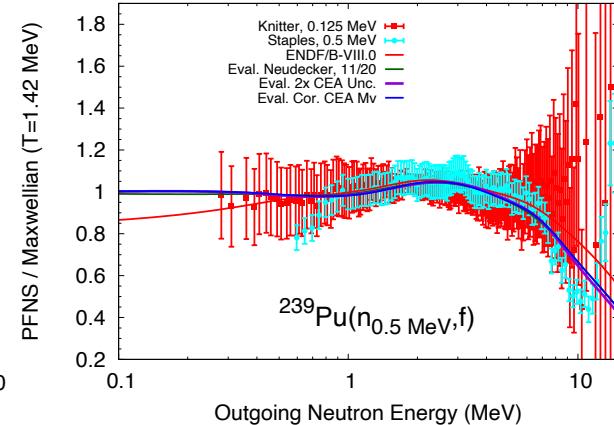
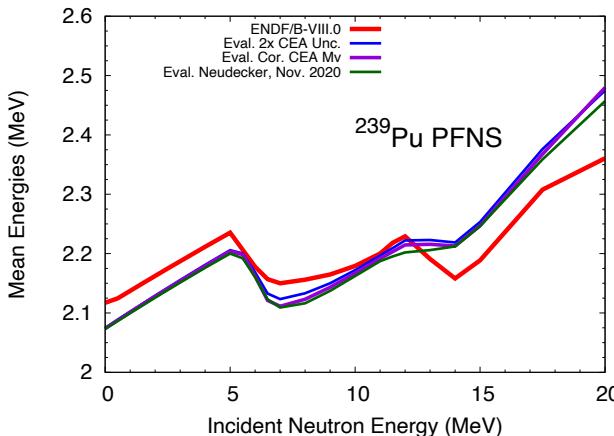
nu-bar

PFNS

# One previous version: Chi-Nu & CEA distinctly change eval.



# $^{239}\text{Pu}(n,f)$ PFNS I: One previous version

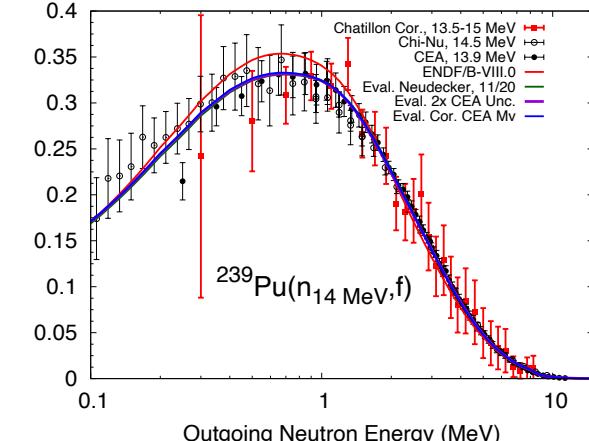
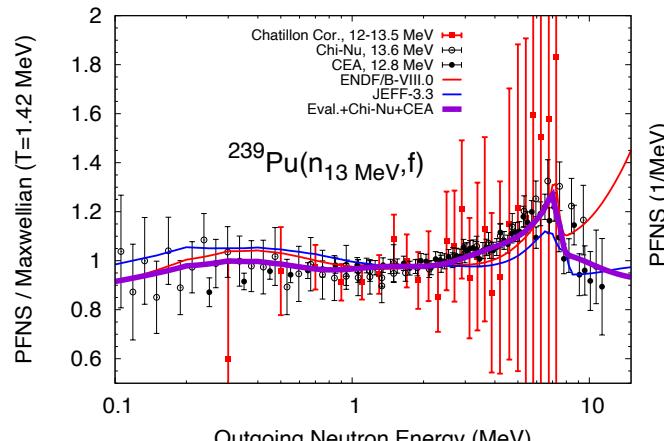
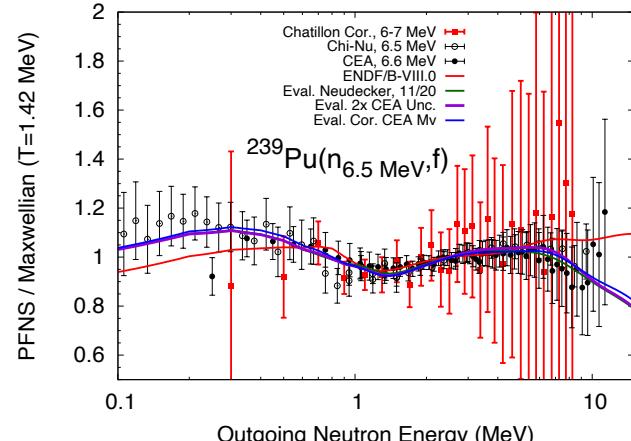
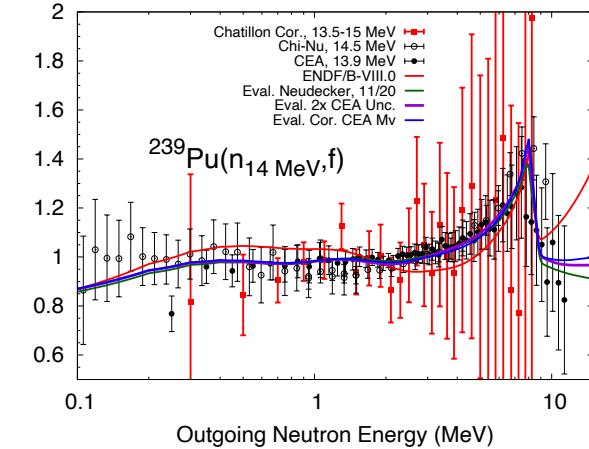
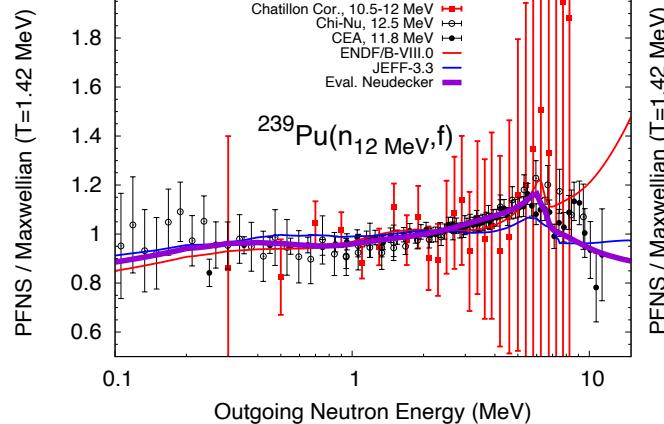
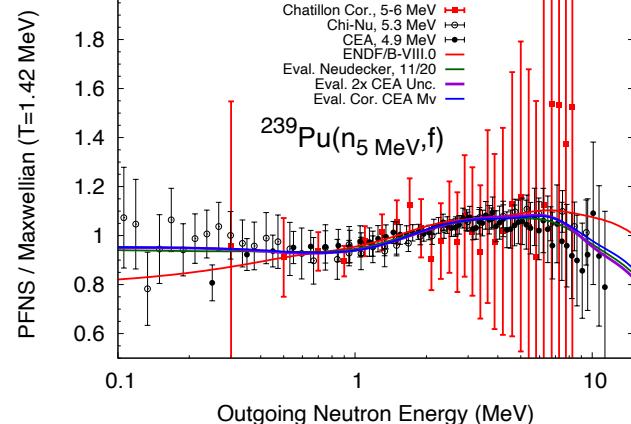


PFNS

nu-bar

(n,f) cross section

# $^{239}\text{Pu}(n,f)$ PFNS II: One previous version



PFNS

nu-bar

(n,f) cross section